

From Hill Cutting to Landslide: Understanding Failure of Himalayan Road Slope

Sarada Prasad Pradhan ^{1*}

¹Department of Earth Sciences, Indian Institute of Technology (IIT) Roorkee

*(Corresponding E-mail: sppradhan@es.iitr.ac.in)

Abstract: The expansion and widening of transportation corridors across the Himalaya require extensive excavation of steep and geologically complex mountain slopes, increasing the potential for slope instability. This review examines rock cut slope stability along major transportation corridors, including NH-58, NH-7, and NH-09. The reviewed studies indicate that hill cutting modifies natural slope equilibrium through toe excavation, slope steepening, increased slope height, uncontrolled blasting, and the development of secondary fractures. Weathering and groundwater infiltration further deteriorate rock mass conditions and contribute to instability. Slope stability is influenced by multiple factors across different spatial scales. At the slope scale, height, inclination, cohesion, and friction angle influence stability, while discontinuity orientation, persistence, spacing, roughness, and connectivity govern structurally controlled rock failures. Empirical classification systems, including RMR, SMR, CSMR, GSI, and Q-slope, support preliminary assessments, while kinematic analysis identifies potential failure mechanisms. Numerical methods, including LEM, FEM, FDM, and DEM, facilitate stability evaluation and failure modelling. Recent developments in microstructural analysis and Discrete Fracture Network modelling improve the representation of rock mass heterogeneity and fracture connectivity. The review emphasizes geologically informed excavation, appropriate slope geometry, controlled blasting, systematic investigation, and continuous monitoring to reduce instability and landslide hazards along Himalayan transportation corridors.

Keywords: *Himalayan rock slopes, Slope stability, Hill cutting, Road widening, Discontinuities, Numerical modelling, Landslide hazards, Discrete Fracture Network (DFN).*

Introduction

The expansion and widening of transportation corridors across the Himalayan region are essential for improving regional connectivity and supporting socio-economic development. However, road construction in steep and geologically complex mountainous terrain requires extensive excavation, which can disturb the natural equilibrium of slopes and increase their susceptibility to instability. Hill cutting modifies slope geometry, removes support from the toe, and may introduce additional fractures through uncontrolled blasting and inappropriate excavation techniques. Over time, weathering and groundwater infiltration can further weaken exposed rock surfaces and deteriorate

discontinuity conditions. Studies conducted along major transportation corridors, including NH-58, NH-7, and NH-09, demonstrate the importance of understanding the geological and geotechnical factors controlling slope stability. These factors operate at different spatial scales, ranging from overall slope geometry and rock mass discontinuities to microstructural characteristics. Consequently, evaluating Himalayan road cut slopes requires an integrated approach combining empirical classification systems, kinematic analysis, and numerical modelling. Understanding the relationship between excavation practices, geological structures, and slope behaviour is essential for identifying potential failure mechanisms and developing appropriate slope management strategies.

Factors controlling himalayan road Cut slope stability

The stability of Himalayan road cut slopes is controlled by interacting geological, geotechnical, and excavation-related factors operating at multiple spatial scales. At the slope scale, height and inclination influence stability in both rock and debris slopes. The reviewed investigations indicate that cohesion and friction angle exert a significant influence on the factor of safety of debris slopes, while slope height and angle govern the development of shear strain. Studies along NH-7, NH-58, and NH-09 similarly indicate critical stability conditions in slopes with greater heights and steeper inclinations. At the rock mass scale, discontinuity orientation, persistence, spacing, roughness, and connectivity determine the potential for planar, wedge, and toppling failures. Empirical classification systems, including Rock Mass Rating (RMR), Slope Mass Rating (SMR), Continuous Slope Mass Rating (CSMR), Geological Strength Index (GSI), and Q-slope, provide methods for preliminary stability assessment. Kinematic analysis helps identify structurally feasible failure mechanisms. At the micro-scale, rock microstructures also influence rock mass behaviour. DEM-based research indicates that incorporating microstructures into numerical models can reduce the calculated factor of safety by approximately 10%, demonstrating the importance of considering internal

rock mass characteristics during slope stability analysis.

Numerical modelling and emerging approaches

Numerical modelling has become increasingly important for evaluating slope stability and understanding the development of failure in Himalayan mountain slopes. Methods such as the Limit Equilibrium Method (LEM), Finite Element Method (FEM), Finite Difference Method (FDM), and Discrete Element Method (DEM) provide different approaches to analysing slope behaviour under varying geological and geotechnical conditions. The reviewed case studies apply the Generalized Hoek–Brown and Mohr–Coulomb failure criteria to assess rock slope stability, while the Barton–Bandis method is used to represent joint behaviour. Although these approaches support the evaluation of slope stability, conventional rock mass characterization and two-dimensional analyses may not fully represent the complexity of fractured rock masses. Discrete Fracture Network (DFN) modelling provides an approach for representing fracture connectivity, block size, and rock mass heterogeneity in three dimensions. Additionally, DEM-based analyses incorporating microstructural features demonstrate how internal rock characteristics can influence calculated stability. These developments support more detailed investigations of potential failure mechanisms and the influence of geological discontinuities. Integrating numerical modelling with geological investigations, empirical classification, and kinematic analysis can improve the assessment of slope instability along Himalayan transportation corridors.

Conclusion

The reviewed studies demonstrate that hill cutting and road widening significantly influence the stability of mountain slopes along Himalayan transportation corridors. Excavation can remove essential toe support, increase slope height and inclination, and disturb existing geological discontinuities, while uncontrolled blasting may create additional fractures that facilitate rock failure. Weathering and groundwater infiltration can further weaken exposed rock masses and increase instability over time. Slope behaviour is governed by interacting factors across multiple scales, including slope geometry, rock mass discontinuities, and microstructural characteristics. Empirical classification systems, kinematic analysis, and numerical modelling provide complementary approaches for evaluating these conditions, while DFN modelling offers improved representation of fracture connectivity and rock mass heterogeneity. The reviewed research also highlights the importance of appropriate excavation methods and systematic geological and geotechnical investigations. Therefore, effective management of Himalayan road cut slopes should

prioritize geologically informed hill cutting, suitable slope geometry, controlled excavation and blasting, appropriate stabilization measures, and systematic monitoring. Identifying potential instability before it develops into a hazardous landslide is essential for improving slope safety and maintaining the integrity of transportation infrastructure across the Himalayan region.